An Excavator Simulator for Determining the Principles of Operator Efficiency for Hydraulic Multi-DOF Systems

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ABSTRACT
This paper discusses an excavator simulator constructed to evaluate the effects of human-machine interfaces (HMIs) on operator productivity. Simulation allows for standardization of the machine and environment and is less time consuming and cheaper than implementing the controller on the machine. The simulator discussed in this paper includes a realistic graphical display that exceeds the current academic simulators, audio, and a new soil model that accounts for all possible trajectories of the bucket through the soil. Two coordinated control schemes were implemented on the simulator and preliminary tests were performed to demonstrate that the simulator can be used to evaluate HMIs.

INTRODUCTION

Mobile, multi-degree of freedom, hydraulic equipment commonly used in construction, agriculture, mining, and forestry has non-intuitive kinematics that require extensive operator training and experience to perfect. Industry studies show that even experienced operators continually make small errors when operating such equipment because of the large cognitive load[1)]. By reducing the number of operator errors, more intuitive human machine interfaces (HMIs) can boost operator efficiency, or in other words, allow the operator to complete the same task in less time. This causes greater productivity and fuel efficiency.

Coordinated control and other methods have been applied to multi-DOF systems, fluid-powered or otherwise, and have been shown to increase operator control and efficiency[2)]. These studies implement the HMI without regard to the dynamics of the system being controlled. No in-depth research has been done on what underlying control principles are best used to maximize operator efficiency specifically for mobile hydraulic equipment. This paper outlines a simulator developed to study human-machine interfaces designed for such multi-DOF machines in order to research what control laws and feedback are best suited for off-road hydraulic equipment to maximize operator efficiency. Another novel aspect of this simulator is that instead of examining the standard valve controlled machines, the excavator modeled and tested in this paper is a variable displacement pump controlled machine[3)]. The dynamics of the pumps are markedly different from valves and using pumps eliminates throttling losses. In addition to the modeling and construction of the simulator, four control schemes with different types of coordinated control and haptic feedback were compared in a small proof-of-concept test to demonstrate that the simulator can successfully be used to measure operator efficiency.

To test HMIs, the standard and new interfaces must be tested against one another on machines doing the same task in the same environment. Changing the controls on a real machine is time consuming and can be expensive. In order to bypass these difficulties, simulators are constructed so that different HMIs can easily be switched in and out for testing purposes. Simulation also allows the environment to be standardized for all tests. The simulator discussed in this paper is a pump controlled Bobcat mini-excavator. A realistic graphical interface is written that exceeds the quality of current academic simulators. The graphical interface is placed together with dynamic models of the excavator's hydraulic and mechanical systems developed from manufacturer data, into the cab of the mini-excavator. A new soil model was created to incorporate all possible motions of the bucket through the soil in order to realistically reflect the dynamics of the bucket-soil interaction.

Two coordinated control schemes are developed and preliminary tests are run to measure increases in operator effectiveness and machine fuel efficiency. Force feedback is applied to both of the coordinated control schemes and the effectiveness and efficiency increases are measured again, to show that the operator workstation can be used to test new HMIs.

excavator Simulator Architecture

The simulator consists of two main sections, the operator workstation and the control station. The operator workstation is built in the cab of a Bobcat 435 excavator, the same model of excavator used by the simulation. During testing, the subject operates the simulated bobcat from this workstation. The control station consists of three networked computers that perform the simulation and allow the test-giver to vary parameters and record data.

Operator Workstation - The operator workstation is the cab of a Bobcat 435 excavator that has been retrofitted with multiple input devices. The standard hydraulic joysticks were removed and a Phantom joystick was mounted inside the cab on a new shelf. The arm of the excavator was removed to allow a 132 cm (52 inch) LCD screen to be mounted directly in front of the windshield. The simulated arm and environment are displayed on the screen (see *Figure 1* and *Figure 3*). The trench is clearly demarcated in flat green so that subjects know where in the grass to excavate.

Figure 1: Operator workstation

Control Station - The control station is the computing heart of the simulation and comprises of three computers, the Phantom PC, the xPC target, and the Main PC. The Control PC interfaces with the Phantom joystick or other input devices. The Main PC renders the graphics on the LCD screen, stores data, loads the

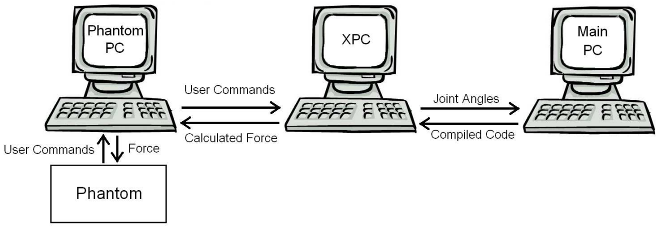

Figure 2: Control station’s computer network

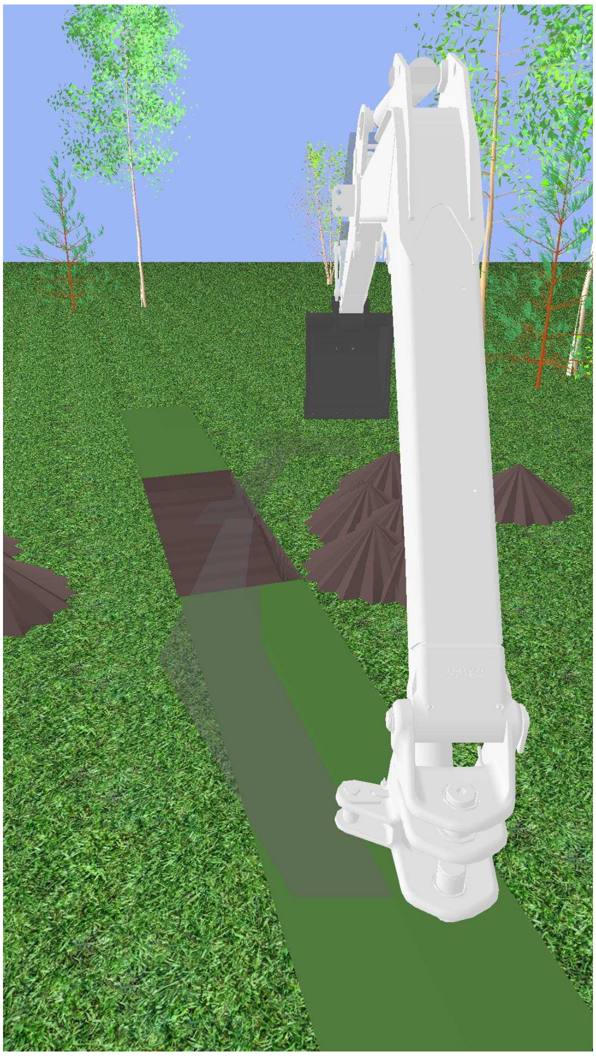
Figure 3: Operator workstation and simulator screenshot
Simulink model to the xPC target, and allows the test-giver to change the simulator. The xPC target simulates the dynamics of the excavator's hydraulic and mechanical system and computes the dynamic interaction between the excavator and the soil. The xPC target also calculates the haptic feedback forces and sends them to the Phantom PC. The three computers are connected via Ethernet cards and a hub.

Input device

Phantom Joystick - The standard two 2-DOF joysticks were replaced with a single Phantom Premium 1.0 haptic joystick (referred to in this paper as a Phantom) manufactured by Sensable Technologies. The Phantom has three degrees of freedom and three degrees of force feedback. The gimbal attachment, essentially a three degree of freedom wrist, was connected to give a total of six degrees of freedom. Only four degrees of freedom are used to control the excavator. The location of the wrist of the Phantom corresponds to the motion of the wrist of the excavator and the rotation about one of the axes of the Phantom's gimbal corresponds to the curl of the excavator's bucket.

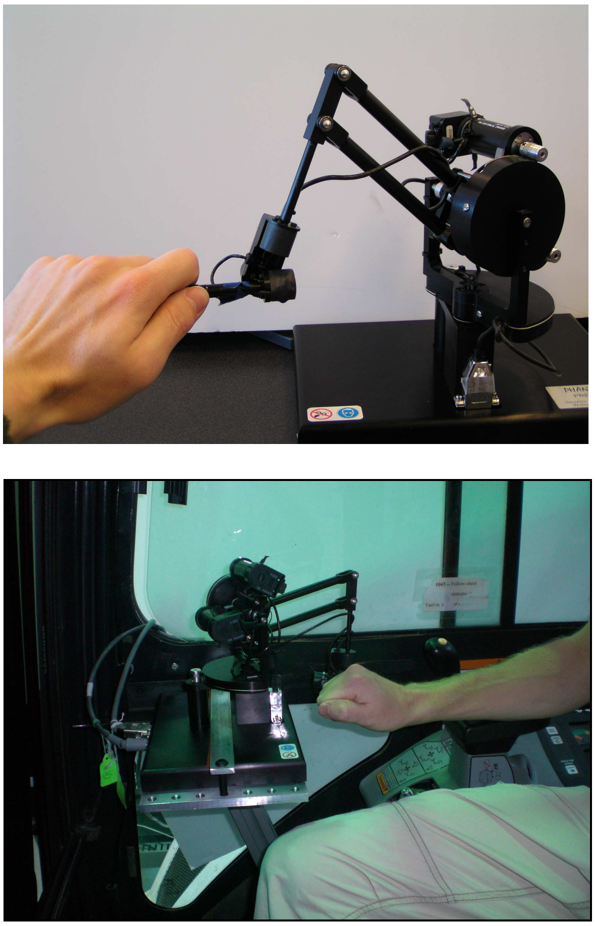

Figure 4: Sensable Phantom Premium 1.0 mounted out- and inside the cab

Input Control Modes - Two different coordinated control modes were implemented using the Phantom – position control mode and hybrid control mode.

<u>Position Control Mode</u> - When the Phantom is in position control mode the position of the wrist of the Phantom corresponds to the position of the wrist of the excavator. Although the Phantom has a similar kinematic construction to the excavator, the Phantom is mounted facing the operator so that the excavator mimics the operator's arm motions rather than the Phantom's configuration. This means that as the operator pulls the Phantom's wrist towards himself, the wrist of the excavator moves towards the cab while the Phantom, on the other hand, is extending itself. The scaled workspace of the Phantom exceeds the workspace of the excavator, so a limiting algorithm is in place that maps any out-of-bounds locations of the Phantom to the nearest inbounds location for the excavator. Although the cab of the excavator rotates, the axes (shown on the right in *Figure 5*) are globally fixed. The rotation of the handle on the Phantom corresponds to the angular rotation of the bucket

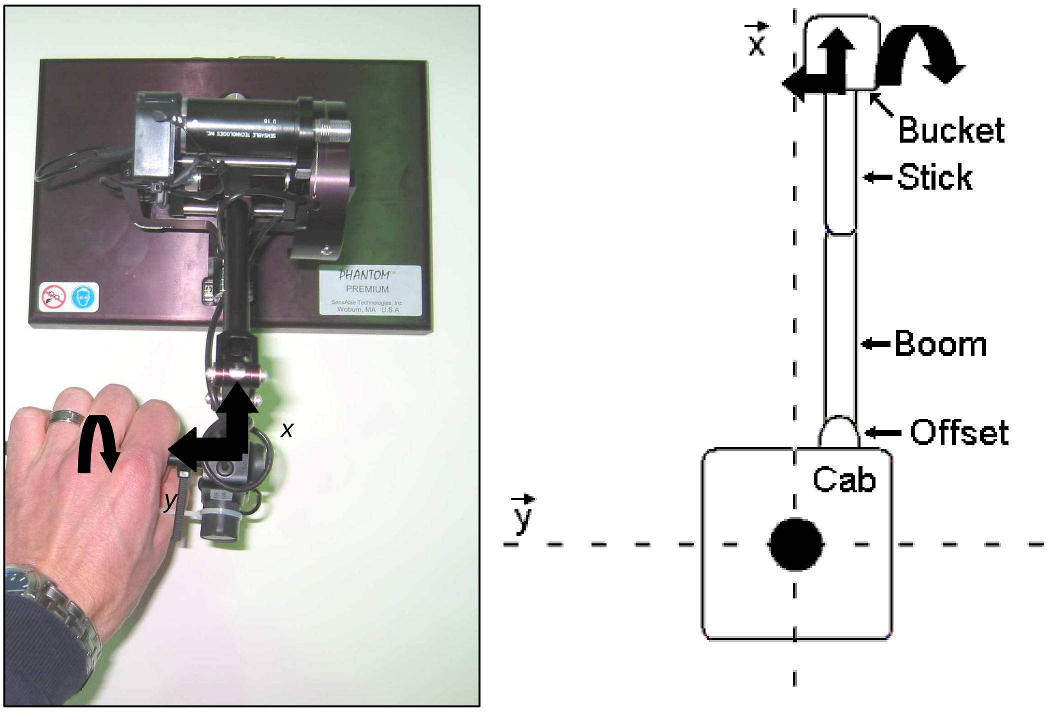

Figure 5: Position control mode from above the Phantom and excavator
In this mode, a force proportional to the forces applied to the bucket can be displayed by the Phantom, which will be called ‘digging force reflection’ in this paper.

<u>Hybrid Control Mode</u> - Hybrid control mode is a mix of velocity and position control. Unlike position control mode, the axes of the Phantom rotate with the cab and are therefore better defined as cylindrical rather than Cartesian coordinates. In the radial and vertical directions, position control is used. Displacements in the theta-direction (left and right to the operator) correspond to the angular velocities of the cab. As in position control, the position of the handle corresponds to the rotation of the bucket. A deadband is programmed into the software so that the operator can easily command zero velocity (see the dashed lines in *Figure 6*)

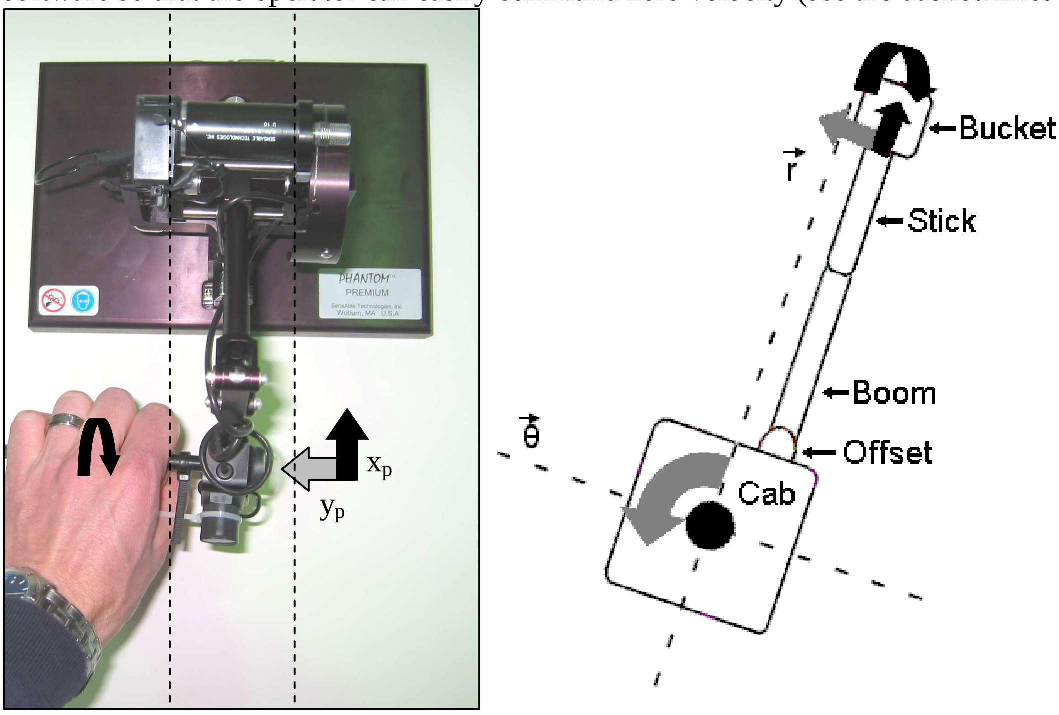

Figure 6: Hybrid control mode from above the Phantom and excavator

In this mode, digging force reflection can be enabled or disabled, and there is also a spring return force in the theta-direction much like in standard joystick. This force is always present in hybrid mode so that the operator knows when he is in the deadband.

HUman factors testing

In order to ascertain the feasibility of using this simulator to evaluate novel HMIs, a small study was done with six subjects to see if it was possible to collect meaningful data using the simulator.

Test Procedure - It was explained to each subject how the simulation works and how the position and hybrid controllers were different. The subject was then given two minutes with each controller to experience the difference. Digging force reflection was explained and then the subject was given two more minutes in each input mode with the digging force reflection enabled. The subject was then told that his primary goal was to remove as much dirt as possible from the trench. Along with the primary goal, two secondary goals of lesser importance were assigned: to place dumped dirt in a large pile (i.e. dump each bucket load of dirt as close as possible to the previous ones) and to enter the trench cleanly without touching the soil to the left or right of the trench. The amount of energy used by each subject for each trial was also recorded, but the subjects were not told to be energy efficient.
The subjects then were given two minutes with each of the following modes to accomplish the given goals: position control, hybrid control, position control with digging force reflection, hybrid control with digging force reflection. Then the process was repeated so that each subject did eight trials – two with each mode. Each subject saw the modes in different orders to minimize learning effects. After all the trials were over, the subjects were given a survey asking their preferences of HMI.

Test Results - The results were analyzed and then normalized with respect to position control mode. The amount of soil removed from the trench was directly recorded. To evaluate pile proximity, the inverse of the standard deviation of the distance of piles from each other was plotted. To measure the subjects' ability to enter the trench unimpeded, the number of times the trench was entered was recorded along with the number of times the operator hit the ground outside the trench. From this data, the percentage of "clean" trench entrances was calculated. Lastly, the amount of soil removed per unit energy was calculated so that in all four measurements, a higher value is better. The error bars are large because of the small set of subjects and trials, but definite trends were apparent. Subjects tended to do better with position control rather than hybrid control with or without digging force reflection.

The subjects' responses to the post-test survey showed a clear preference to position control with digging force reflection. The subjects were asked to rank each of the four control modes from one to four in order of how well they aligned with the statements in *Figure 8*, with four being that it most aligned with statement.

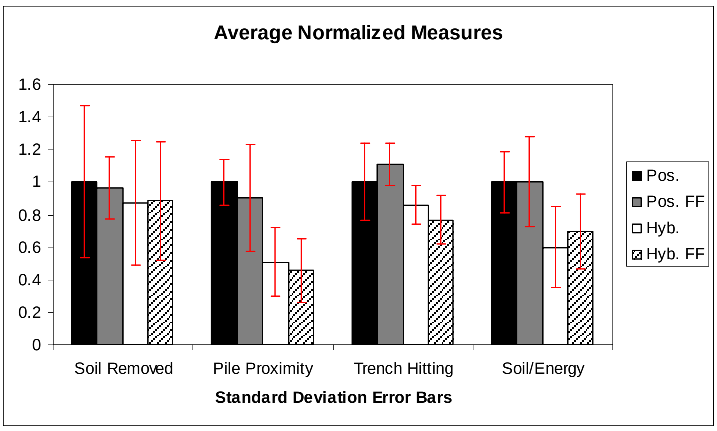

Figure 7: Test results. Pos. and Hyb. correspond to position and hybrid control modes. FF stands for force feedback, in other words, digging force reflection was enabled

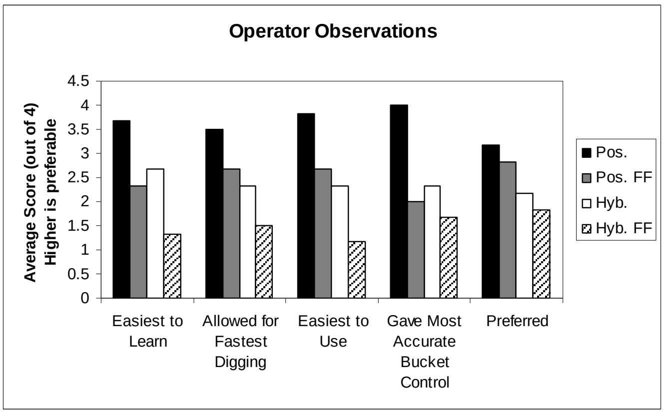

Figure 8: Survey results

Conclusion

The excavator simulator discussed in this paper can be used to evaluate new HMIs. Preliminary tests gave data that showed different HMIs affected operator performance. Future work includes giving larger scale tests and comparing the novel HMIs to the current state of the art interface.

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